The amazing world of String Theory

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String theory is an amazing branch of science that manages to unify all matter and interactions under one simple idea.
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The starting point is the so-called Nambu-Goto action:

\[ S_{NG} = -T \int d^2 \sigma \sqrt{-\det \frac{\partial X^\mu}{\partial \sigma^\alpha} \frac{\partial X^\nu}{\partial \sigma^\beta} \eta_{\mu\nu}} \]
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\]

where \( T \) is the tension of the string, \( \sigma^\alpha \) are the world-sheet coordinates, \( X^\mu \) are the space-time coordinates and \( \eta_{\mu\nu} \) is the flat spacetime metric.
The more useful version is the so-called Polyakov action, that goes in the following way

\[ S = -T \int d^2 \sigma \sqrt{h} h^{\alpha \beta} \partial_\alpha X^\mu \partial_\beta X^\nu \eta_{\mu \nu} \]
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Lets start our talk now.
The more useful version is the so-called Polyakov action, that goes in the following way

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You really didn’t come here to listen to this, did you? I was just kidding!

Let’s start our talk now hopefully I’ll manage to explain what on earth is string theory!
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\[ S = -T \int d^2\sigma \sqrt{h} h^{\alpha\beta} \partial_\alpha X^\mu \partial_\beta X^\nu \eta_{\mu\nu} \]

You really didn’t come here to listen to this, did you? I was just kidding!

Let’s start our talk now hopefully I’ll manage to explain what on earth is string theory! Its also a good time to open your can of draft beer!
From very early on people have been thinking about this:
From very early on people have been thinking about this:
From very early on people have been thinking about this:

Cosmology marches on

Where the hell did it all come from?

In this talk I’ll try aim for this
From very early on people have been thinking about this:

COSMOLOGY MARCHES ON

In this talk I’ll try aim for this hopefully!
But before we start discussing String Theory, some of you might be wondering:
What is String Theory?
What is String Theory?

How does this fit in with what we already know?
What is String Theory?

How does this fit in with what we already know?

Do we really need string theory to answer our fundamental questions?
What is String Theory?

How does this fit in with what we already know?

Do we really need string theory to answer our fundamental questions?

Where did those good old theories go wrong?
Therefore let me start from the very beginning, way down in history, when Classical Mechanics ruled our ideas ...
It All Started With This Book

PHILOSOPHIAE NATURALIS PRINCIPIA MATHEMATICA

AUTORE J S. NEWTONI TRIB. COLV. CAM. SUBC. MATHEMATICI PROFESSORE LUCASIANO, & SOCIETATIS REGIAE SODAL.

IMPRIMATUR:
S. PEPYS, REG. SOC. PRÆS.

JULII 5, 1686.

LONDINI,

JUSSU SOCIETATIS REGIAE AC TYPIS JOSEPHI STreater. PROFIAT APUD PLURES BIBLIOPOLAS. ANNO MDCLXXXVII.
And The Ideas Developed By Him

The Year Was 1687

For almost two centuries the theory developed by Newton (and others) ruled supreme. However, towards the beginning of the 20th century people started finding cracks in the edifice...
And The Ideas Developed By Him

The Year Was 1687
The Year Was 1687

For almost two centuries the theory developed by Newton (and others) ruled supreme. However towards the beginning of the 20th century people started finding cracks in the edifice ...
These cracks came from two regions.
These cracks came from two regions

- Exploring very high speeds
These cracks came from two regions

- Exploring very high speeds
- Exploring very short distances
So First: What happens when we explore short distances?
It is now known that the theory there should be Quantum Mechanics whose main result can be summarised by one line.
Nature is probabilistic i.e.
Uncertainty rules supreme
Nature is probabilistic i.e.
Uncertainty rules supreme
or, more appropriately, just like
coin toss! Before you toss the
coin you’ll never know the
outcome!
The former idea was proposed by Erwin Schrodinger
The former idea was proposed by Erwin Schrödinger.
And the latter idea was presented by Werner Heisenberg
And the latter idea was presented by Werner Heisenberg
Quantum mechanics is a strange theory which, fortunately, is visible only at very short distances! If it was visible at large distances, then we would see the following:
Quantum mechanics is a strange theory which, fortunately, is visible only at very short distances! If it was visible at large distances, then we would see the following:
Quantum mechanics is a strange theory which, fortunately, is visible only at very short distances! If it was visible at large distances, then we would see the following:
Which means we would never be sure if the cat is dead or alive, unless we make a measurement!
Which means we would never be sure if the cat is dead or alive, unless we make a measurement! Much like:
Which means we would never be sure if the cat is dead or alive, unless we make a measurement! Much like:

Schrödinger's cat is ALIVE
The previous observation is generically represented in the following way that distinguishes Newtonian theory from Quantum mechanics.
The previous observation is generically represented in the following way that distinguishes Newtonian theory from Quantum mechanics.
These were all developed around 1927
These were all developed around 1927

It was the best of times and it was the worst of times!
These ideas were very beautiful, and very very revolutionary. At that time the key person who really understood both these ideas was Neils Bohr.
These ideas were very beautiful, and very very revolutionary. At that time the key person who really understood both these ideas was

Neils Bohr
In fact he understood the subject so well that he made the following comment
In fact he understood the subject so well that he made the following comment

“If Quantum Mechanics hasn’t profoundly shocked you, you haven’t understood it yet!”
Although relatively not well publicised, it seem he also made the following comments:
Although relatively not well publicised, it seem he also made the following comments:

“If you don’t understand Quantum Mechanics
Although relatively not well publicised, it seem he also made the following comments:

“If you don’t understand Quantum Mechanics, Erwin Schrödinger will kill you like a cat in a box. Maybe.”
But then there was one person who was really disturbed by Quantum Mechanics
But then there was one person who was really disturbed by Quantum Mechanics.
Einstein said
Einstein said

Quantum Mechanics cannot be the right theory of nature, because it is hard to believe that God plays with dice!
To which Bohr replied
To which Bohr replied

Einstein, stop telling God what to do!
But then why was Einstein so disturbed?
But then why was Einstein so disturbed?

Because he had, towards the beginning of the 20th century, developed two theories that modifies classical mechanics at high speeds
But then why was Einstein so disturbed?

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Special Theory of Relativity: at uniform speeds
But then why was Einstein so disturbed?

Because he had, towards the beginning of the 20th century, developed two theories that modifies classical mechanics at high speeds.

Special Theory of Relativity: at uniform speeds

General Theory of Relativity: at non-uniform speeds
The GTR views the spacetime as rubber sheets on which masses form dents.
The GTR views the spacetime as rubber sheets on which masses form dents.
So gravity is simply a distortion of geometry!
So gravity is simply a distortion of geometry!
For Einstein this was nice and elegant because everything was precise and there was no ambiguity or uncertainty...
For Einstein this was nice and elegant because everything was precise and there was no ambiguity or uncertainty...

Yet Quantum Mechanics was right, so was General Theory of Relativity!
So what's going on? Does nature behave differently as we explore different limits?
To investigate this first let us go to the limit where we can have
To investigate this first let us go to the limit where we can have
- Short Distances
+ High Speeds
To investigate this first let us go to the limit where we can have Quantum Mechanics + High Speeds
To investigate this first let us go to the limit where we can have Quantum Mechanics + Special Theory of Relativity.
To investigate this first let us go to the limit where we can have

Quantum Mechanics
+ Special Theory of Relativity
= QUANTUM FIELD THEORY
The special theory of relativity is based on the fact that the speed of light is the highest speed and is a constant. This leads to:
The special theory of relativity is based on the fact that the speed of light is the highest speed and is a constant. This leads to:

**Time dilation**
The special theory of relativity is based on the fact that the speed of light is the highest speed and is a constant. This leads to:

Time dilation
And length contraction
And length contraction
Take 1: Let's mix QM with STR
Take 1: Let's mix QM with STR
Take 1: Let's mix QM with STR

What do we really get?
Well ...
Well ...
Well ...

More appropriately: disaster!
What did we miss?
What did we miss?
After much confusion
What did we miss?
After much confusion
What did we miss?
After much confusion and anger..
What did we miss?
After much confusion
and anger..
It was eventually suggested by Feynman.
It was eventually suggested by Feynman and others...
Quantum Mechanics + STR + Renormalisation
Quantum Mechanics + STR + Renormalisation

= Something really nice and consistent
Quantum Mechanics + STR + Renormalisation

= Something really nice and consistent

For example QED: Quantum Electrodynamics
For those who don’t know anything about renormalisation, the idea is very simple!
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For those who don’t know anything about renormalisation, the idea is very simple! You do a calculation, and say you get an infinite answer. Then you bring another infinity and do the following:

\[ \text{Infinity} - \text{Infinity} = \text{finite} \]
For those who don’t know anything about renormalisation, the idea is very simple! You do a calculation, and say you get an infinite answer. Then you bring another infinity and do the following:

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For those who don’t know anything about renormalisation, the idea is very simple! You do a calculation, and say you get an infinite answer. Then you bring another infinity and do the following:

\[ \text{Infinity} - \text{Infinity} = \text{finite} \]
Well it works, that's what matters, right?
Well it works, that's what matters, right? After you have "understood" renormalisation i.e. if you are in the following state:
Well it works, that's what matters, right? After you have “understood” renormalisation i.e. if you are in the following state:
This would make life very simple!
This would make life very simple!
So simple that we bring the cook again and mix QM + General Theory of Relativity + Renormalisation
This should give us the ultimate nice theory that explains everything!
This should give us the ultimate nice theory that explains everything!

So what do we get?
Unfortunately
Unfortunately

What went wrong now??
After much thinking
After much thinking
And this time it required a lot of thinking!
After much thinking
And this time it required a lot of thinking!
It was realised that the problem was created by point particles.
It was realised that the problem was created by point particles. Thus point particles have to be replaced by vibrating strings!
To understand how string theory changes the interaction “diagrams”, let us first draw a space-time picture.
To understand how string theory changes the interaction “diagrams”, let us first draw a space-time picture.
This means that the “Feynman diagram” would be the following
This means that the “Feynman diagram” would be the following
The corresponding string diagrams would be
The corresponding string diagrams would be:

(a) X, or ...
(b) Y, or ...
(c) Z, or ...
(d)
The corresponding string diagrams would be:

(a) X, or...
(b) Y, or...
(c) Z, or...
(d) A

(e) One-loop Feynman diagrams for point particles
(f) Corresponding closed-string diagrams of same topology
Such a situation should get rid of all the problems and nothing should blow up again!
Such a situation should get rid of all the problems and nothing should blow up again!

Thus string theory was born.
Such a situation should get rid of all the problems and nothing should blow up again!

Thus string theory was born.

This was around 1970
Soon with the effort of many physicists the first concrete string model was built
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John Schwarz
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Michael Green
Soon with the effort of many physicists the first concrete string model was built.

John Schwarz

Michael Green
Soon with the effort of many physicists the first concrete string model was built.
This was called the **bosonic string theory** because the interacting particles were all bosons.
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**Satyendranath Bose**

![S N Bose (1894-1974)](image)
This was called the **bosonic string theory** because the interacting particles were all bosons. Bosons are particles that look the same no matter from what direction you are looking at! They were developed mainly by **Satyendranath Bose** and **Albert Einstein**.
This was called the **bosonic string theory** because the interacting particles were all bosons. Bosons are particles that look the same no matter from what direction you are looking at! They were developed mainly by [Satyendranath Bose](#) and [Albert Einstein](#).
On the other hand there are particles that look different when you rotate them! They are called fermions. They were developed by Paul Dirac and Enrico Fermi.
On the other hand there are particles that look different when you rotate them! They are called **fermions**. They were developed by Paul Dirac and Enrico Fermi.
On the other hand there are particles that look different when you rotate them! They are called fermions. They were developed by Paul Dirac and Enrico Fermi.
The fermions also satisfy the Pauli Exclusion Principle, developed by Wolfgang Pauli
The PEP says that no two fermions like each other!
The PEP says that no two fermions like each other!
The PEP says that no two fermions like each other!
However the string theory that we developed had three sides:
However the string theory that we developed had three sides: The Good, The Bad and The Ugly!
The Good

The Good Theory reproduces Einstein's General Theory of Relativity. The theory doesn't blow up and seemed perfectly consistent with Quantum Mechanics. It predicts the existence of gravity particles called gravitons, much like the bosons that we discussed.
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The Good

- Theory reproduces Einstein's General Theory of Relativity

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String Theory

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The Good

- Theory reproduces Einstein General Theory of Relativity
- Theory doesn’t blow up
The Good

- Theory reproduces Einstein General Theory of Relativity
- Theory doesn’t blow up
- Seemed perfectly consistent with Quantum Mechanics
The Good

- Theory reproduces Einstein's General Theory of Relativity
- Theory doesn’t blow up
- Seemed perfectly consistent with Quantum Mechanics
- Predicts the existence of gravity particles called gravitons, much like the bosons that we discussed
The Bad

Predicts the existence of twenty-six space-time dimensions.

Any other lower/higher dimensions we face are inconsistent.

Our observable universe is 3+1 dimensions, so we need to account for 22 extra dimensions.
The Bad

Predicts the existence of twenty-six space-time dimensions. Any other lower/higher dimensions we face would be inconsistent. Our observable universe is 3+1 dimensions, so we need to account for 22 extra dimensions.
The Bad

- Predicts the existence of twenty-six space-time dimensions

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String Theory

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The Bad

- Predicts the existence of twenty-six space-time dimensions
- Any other lower/higher dimensions we face inconsistency
The Bad

- Predicts the existence of twenty-six space-time dimensions
- Any other lower/higher dimensions we face inconsistency
- Our observable universe is 3+1 dimensions, so we need to account for 22 extra dimensions
The theory has an imaginary mass particle, also known as the Tachyon that moves faster than light, violating STR. So at best the theory is not well defined in the present form, but could be ok if certain modifications are made. At worst, we have got the wrong theory.
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The theory has an imaginary mass particle, also known as the Tachyon that moves faster than light, violating STR. So at best the theory is not well defined in the present form, but could be ok if certain modifications are made. At worst, we have got the wrong theory.
What did we miss now?
What did we miss now?

Well, we haven’t exploited one possible property of the particles
What did we miss now?

Well, we haven’t exploited one possible property of the particles:

The existence of supersymmetry as a possible new symm!
Supersymmetry is based on the following idea
Supersymmetry is based on the following idea
This is of course a conjecture and can only be proved experimentally
This is of course a conjecture and can only be proved experimentally.

But let us assume that it is true...
So we bring our cook back and add all the ingredients
So we bring our cook back and add all the ingredients

Strings + Supersymmetry
So we bring our cook back and add all the ingredients. What do we get now?
We get this
We get this
We get this or this ..
We get this or this ..
.. Or more completely, this
.. Or more completely, this
Good thing is that nothing seems to blow up now.
Good thing is that nothing seems to blow up now

But then, what is it?
To understand the last picture, let us take a simpler model:
To understand the last picture, let us take a simpler model:
To understand the last picture, let us take a simpler model:

The picture represents a sphere at every point on a base.
To understand the last picture, let us take a simpler model:

The picture represents a sphere at every point on a base.

Now identify the base with our four dimensional universe.
This is therefore a representation of a six-dimensional space
This is therefore a representation of a six-dimensional space where the compact sphere is two-dimensional and the base is four dimensional. In other words:
This is therefore a representation of a six-dimensional space where the compact sphere is two-dimensional and the base is four dimensional. In other words:

\[ 6 = 4 + 2 \]
For those who are still thinking about what's going on, here it is again.
For those who are still thinking about what's going on, here it is again.

Reducing dimensions of a space can be achieved by pasting its edges together and shrinking it. For example, a two-dimensional sheet of rubber is first curled into a cylinder, and the curled dimension is then shrunk. When thin enough, the cylinder looks like a (one-dimensional) line. Twisting around this length of "hose" and sticking its ends together, one gets a doughnut shape. The radius of the doughnut can be shrunk until it is small enough to approximate a point—a zero-dimensional space. Such changes could explain why the extra dimensions of space-time that string theory says must exist are too small to be detectable.
For those who are still thinking about what's going on, here it is again.

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The above set of ideas were in fact developed much before string theory by Theodor Kaluza and Oskar Klein, around 1919, that even Einstein tried to implement in his theory!
The above set of ideas were in fact developed much before string theory by Theodor Kaluza and Oskar Klein, around 1919, that even Einstein tried to implement in his theory!
Now comes the most important equation of string theory:

\[ 10 = 4 + 6 \]

where 6 is now the compact internal space fibered over our 3+1 dimensional universe.
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\[ 10 = 4 + 6 \]
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where 6 is now the compact internal space fibered over our 3+1 dimensional universe
Now comes the most important equation of string theory:

\[ 10 = 4 + 6 \]

where 6 is now the compact internal space fibered over our 3+1 dimensional universe
Therefore string theory + supersymmetry predicts $26 \rightarrow 10$ spacetime dimensions.

Cannot be lower than 10, but could be increased to 11, and not more!

Therefore a 10 dim supersymm universe without tachyon with 3+1 dimensional non-compact space (where we live) and a six-dimensional internal space called a Calabi-Yau manifold.
Therefore string theory + supersymmetry predicts

26 spacetime dimensions $\rightarrow$ 10 spacetime dimensions.
Therefore string theory + supersymmetry predicts

26 spacetime dimensions $\rightarrow$ 10 spacetime dimensions. Cannot be lower than 10, but could be increased to 11, and not more!
Therefore string theory + supersymmetry predicts 26 spacetime dimensions $\rightarrow 10$ spacetime dimensions. Cannot be lower than 10, but could be increased to 11, and not more!

Therefore a 10 dim supersymmm universe **without tachyon** with 3+1 dimensional non-compact space (where we live) and a six-dimensional internal space called a **Calabi-Yau manifold**.
Therefore string theory + supersymmetry predicts

26 spacetime dimensions $\rightarrow$ 10 spacetime dimensions. Cannot be lower than 10, but could be increased to 11, and not more!

Therefore a 10 dim supersymm universe without tachyon with 3+1 dimensional non-compact space (where we live) and a six-dimensional internal space called a **Calabi-Yau manifold**
The mathematical structures of these manifolds were developed by
The mathematical structures of these manifolds were developed by Eugenio Calabi.
The mathematical structures of these manifolds were developed by Eugenio Calabi.
The mathematical structures of these manifolds are developed by Shing-Tung Yau.
The mathematical structures of these manifolds are developed by

[Image of a person]
The mathematical structures of these manifolds are developed by Shing-Tung Yau.
However with all the heavy mathematical machinery one might be feeling a bit
However with all the heavy mathematical machinery one might be feeling a bit confused.
However with all the heavy mathematical machinery one might be feeling a bit confused.
However with all the heavy mathematical machinery one might be feeling a bit confused
However with all the heavy mathematical machinery one might be feeling a bit confused.
Help was on the way!

Because far in the west Joe Polchinski at UCSB was thinking of an alternative scenario.
Help was on the way!

Because far in the west Joe Polchinski at UCSB was thinking of an alternative scenario.
Help was on the way!

Because far in the west Joe Polchinski at UCSB was thinking of an alternative scenario
He asked: What if there could be slices of spacetime embedded in our ten-dimensional space?
He asked: What if there could be slices of spacetime embedded in our ten-dimensional space?

In other words we could be on a 3+1 dim slice floating in a ten dimensional space!
He asked: What if there could be slices of spacetime embedded in our ten-dimensional space?

In other words we could be on a 3+1 dim slice floating in a ten dimensional space!
These slices could move and could have any dimensions
These slices could move and could have any dimensions

These slices were called D-Branes
These slices could move and could have any dimensions

These slices were called D-Branes
These slices could move and could have any dimensions. These slices were called D-Branes.

In this language, we could be living on a three brane!
This idea was so popular that Lisa Randall and Raman Sundrum almost immediately proposed a model for an alternative to compactification
This idea was so popular that Lisa Randall and Raman Sundrum almost immediately proposed a model for an alternative to compactification.
This idea was so popular that Lisa Randall and Raman Sundrum almost immediately proposed a model for an alternative to compactification.
They toyed with the idea that maybe we don’t need any Calabi-Yau manifolds to understand our universe. A simple three-brane would be enough because we would live on this surface!
They toyed with the idea that maybe we don’t need any Calabi-Yau manifolds to understand our universe. A simple three-brane would be enough because we would live on this surface!
This picture led to numerous works in our field
This picture led to numerous works in our field but...
This picture led to numerous works in our field but

Unfortunately (or fortunately) such a simple idea doesn’t quite work ...
What seems to work well is when D-branes are mixed with Calabi-Yau manifolds.
What seems to work well is when D-branes are mixed with Calabi-Yau manifolds.
In fact miraculous results can come out by this mixing as shown by these people
In fact miraculous results can come out by this mixing as shown by these people.

Juan Maldacena
In fact miraculous results can come out by this mixing as shown by these people.

Juan Maldacena

Matt Strassler
In fact miraculous results can come out by this mixing as shown by these people

Juan Maldacena
Matt Strassler
Igor Klebanov
Conclusion

I conclude by showing the following figures that capture the essence of my talk.

It all started with this book:

Dasgupta (McGill) String Theory

Homer2012
Conclusion

I conclude by showing the following figures that capture the essence of my talk.

It all started with this book.
Conclusion

I conclude by showing the following figures that capture the essence of my talk.

It all started with this book.
I conclude by showing the following figures that capture the essence of my talk which eventually led to

It all started with this book
I conclude by showing the following figures that capture the essence of my talk

which eventually led to

It all started with this book
Therefore in the second phase it all started with the following books
Therefore in the second phase it all started with the following books
Therefore in the second phase it all started with the following books

Superstring theory
VOLUME 1
INTRODUCTION

M. B. GREEN, J. H. SCHWARZ & E. WITTEN
CAMBRIDGE MONOGRAPHS ON
MATHEMATICAL PHYSICS

Superstring theory
VOLUME 2
LOOP AMPLITUDES, ANOMALIES & PHENOMENOLOGY

M. B. GREEN, J. H. SCHWARZ & E. WITTEN
CAMBRIDGE MONOGRAPHS ON
MATHEMATICAL PHYSICS
Which eventually led us to this
Which eventually led us to this
Till last year there weren’t any positive identification of strings, supersymmetry or extra dimension!
Till last year there weren’t any positive identification of strings, supersymmetry or extra dimension!
Till last year there weren’t any positive identification of strings, supersymmetry or extra dimension!

But recently some subtle hints of supersymmetry has emerged..!
Thank You!
Thank You!

And hopefully it wasn’t too confusing!
Thank You!
And hopefully it wasn’t too confusing!
FIN!